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PRELIMINARY EXPERIMENTS ON THE CLIMATIC EFFECT OF AN INCREASE OF THE ATMOSPHERIC CO_2, USING A THERMODYNAMIC MODEL

J. ADEM*
R. GARDUÑO**
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RESUMEN

Para calcular el calentamiento debido a una duplicación del CO_2 atmosférico, se aplica un modelo termodinámico que incluye el ciclo anual del clima y una capa oceánica mezclada. El modelo usa un enfoque nuevo y simplificado para el tratamiento de las variaciones en el calentamiento introducido al incrementar el CO_2 atmosférico. El aumento promedio anual calculado en el hemisferio norte es de .7°C, con valores de .8°C en primavera y verano y .6°C en invierno y otoño. Sin embargo, cuando las variaciones del calentamiento distinto de radiación (transporte vertical de calor sensible, evaporación en la superficie y condensación de vapor de agua en las nubes) se desprecian, el promedio anual del aumento calculado es 1.4°C. Se demuestra que la capa oceánica mezclada tiene un papel importante en los cálculos.

* *Centro de Ciencias de la Atmósfera, UNAM. 04510 México, D. F.*
** *Facultad de Ciencias, UNAM, 04510 México, D. F.*

ABSTRACT

A thermodynamic model that includes the annual cycle of climate and an ocean mixed layer is applied to compute the warming due to a doubling of the atmospheric CO_2. The model uses a simplified new approach to deal with the variations of the heating introduced by changing the atmospheric CO_2. The computed annual average increase in the Northern Hemisphere is .7°C with values of .8°C in Spring and Summer and .6°C in Winter and Fall. However, when the variations of the heating different from radiation (vertical transport of sensible heat, evaporation at the surface and heat of condensation of water vapor on the clouds) are neglected, the computed annual average increase is 1.4°C. The ocean mixed layer is shown to play an important role in the computations.

INTRODUCTION

Considerable attention has been paid in recent years to the problem of determining the effect of the increase of the atmospheric CO_2 on the climate of the Earth. According to Hoffert (1974), the atmospheric CO_2 will increase in 100% by the year 2025. Bacastow and Keeling (1973) and Marland and Rotty (1974) estimated that this increase will occur by the years 2040 and 2050 respectively.

Due to these estimates, several authors, using a variety of models, have attempted to compute the effect of doubling the atmospheric CO_2 content in the climate of the Earth especially on the surface temperature (Möller, 1973, Manabe and Wetherald, 1967, 1975, 1980; Manabe, 1971; Manabe and Stouffer, 1980; Rasool and Schneider, 1971; Sellers, 1974; Weare and Snell, 1974; Ramanathan, 1981; Ramanathan, Lian and Cess, 1979; Newell and Dopplick, 1979; Gates, Cook and Schlesinger, 1981). There are discrepancies in the results which depend on the model used.

In this paper we compute the effect of doubling the atmospheric CO_2 on the climate, using a northern hemispheric thermodynamic model with a realistic distribution of continents and oceans, which simulates the annual cycle of climate, month by month, and which includes a realistic storage of heat in the oceans.

BRIEF MENTION OF THE MODEL

During the last two decades, with a continued effort, a realistic physical model of climate has been developed (Adem 1962, 1964a,b, 1965a,b, 1970a,b, 1979, 1981, 1982). It is a hemispheric thermodynamic grid model with a resolution intermediate between general circulation models and simple energy balance models. It includes the dynamics in a parameterized way and recently a revised version which is capable of generating the annual cycle of climate became available (Adem, 1982). Such a model offers a new alternative to explore a variety of climate related problems, including the effect of the increase of CO_2.

The model consists of an atmospheric layer of 10 km high, an oceanic layer of a depth of 50 to 100 m.; and a continental layer of negligible depth. The model also includes a layer of clouds and a layer of snow and ice, whose horizontal extents are computed internally.

The basic predicting equation is the conservation of thermal energy which applied to the atmospheric layer and to the ocean (or continent) layer yields two equations which contain as variables the mean atmospheric temperature (T_m) and the surface temperature (T_s), as well as the heating and the transport terms.

The other conservation laws are used diagnostically, together with semi-empirical relations, to parameterize the heating and transport components. These parameterizations supply additional equations which, combined with the thermal energy equations, give rise to a simultaneous system of equations. This is solved with an implicit integration method, yielding, besides the temperatures, the heating functions, the anomalies of wind, and the horizontal extent of cloudiness and of the snow and ice boundary.

The equations and the variables are averaged over a month, so that the transient eddies horizontal transport of heat in the atmosphere is paramaterized using an austausch coefficient equal to $3 \times 10^{10} cm^2 sec^{-1}$.

The snow-ice boundary is carried out as a variable by assuming that it coincides with the 0^oC computed surface isotherm. This is accomplished by an adjusting process between surface albedo and surface temperature by which at each grid point an albedo for snow-ice cover is assigned when the computed surface temperature is lower (or equal) than 0^oC, and an albedo for no snow-ice in the ground is assigned, when the surface temperature is larger than 0^oC, as is described by Adem (1982). This adjusting process converges rapidly due to the snow-ice temperature feedback.

Starting in August, the model is iterated month by month until the difference between the computed anomaly of surface temperature, each month of the last year and the same month of the previous year of the run is smaller or equal to $.01^oC$.

PARAMETERIZATION OF THE ATMOSPHERIC RADIATION

In the model developed and applied previously (Adem 1962) the cloudless atmosphere is assumed to emit as a black body for wave lengths smaller than 8 microns and larger than 13 microns. The region from 8 to 13 microns was assumed to be completely transparent. In order to incorporate the amount of CO_2 as a variable a more refined atmospheric radiation model is needed. We shall assume that the atmospheric content of CO_2 affects the radiation emission only in the wave lengths from 12 to 14 and from 16 to 18 microns.

Kondratyev (1969), using the results of Yamamoto and Sasamori (1958, 1961), gives in a table the mean intensity for each of the 6 intervals of a length of one micron between 12 and 18μ, for different values of the CO_2 concentration. This dependence of the radiation emission on the atmospheric CO_2 content is shown in Fig. 1, where the abscissa is the concentration of CO_2 in cm and the ordinate is the intensity of emission in percent of the black body emission. The curves show the emission corresponding to the one micron interval with which each of them is labeled.

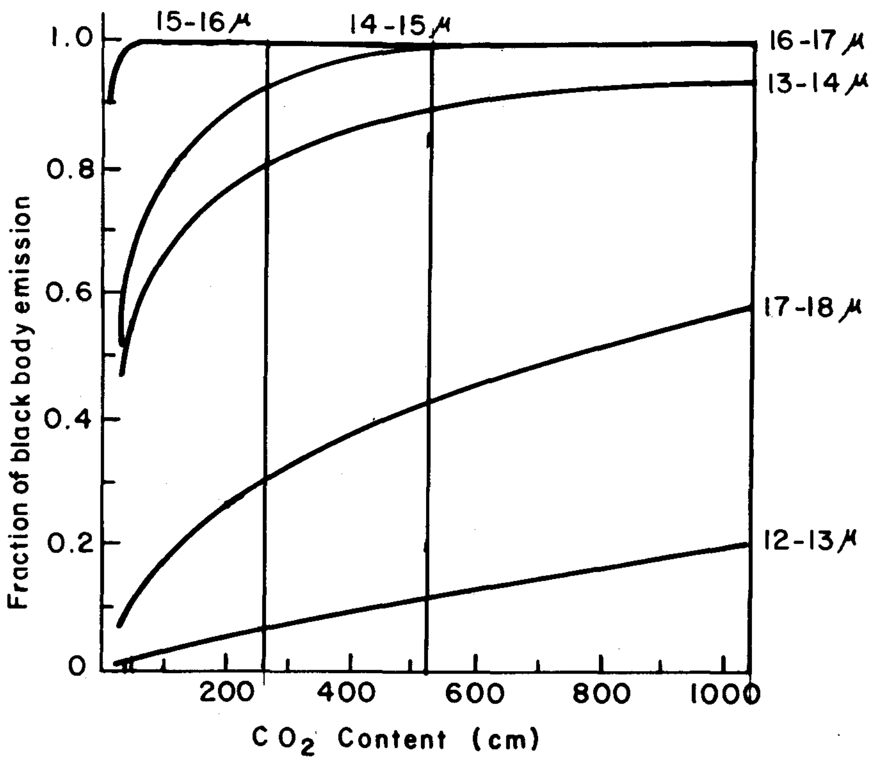


Fig. 1. The abscissa is the concentration of CO_2 in cm. and the ordinate is the intensity of emission in percent of the black body emission. The curves show the emission corresponding to the one micron interval with which each of them is labeled.

Using Fig. 1 we have determined the emission for the present day content of CO_2 (261 cm) and for the case when this value is increased in 100% (522 cm). The values are shown in Fig. 2, where the abscissa is the wave length in microns and the ordinate is the intensity of emission in percent of the black body emission. The shaded area under the continuous line shows the emission for present conditions and the hatched areas show the increase due to doubling the CO_2 content. The hatched and dotted areas show the increase due to quadrupling the CO_2 content.

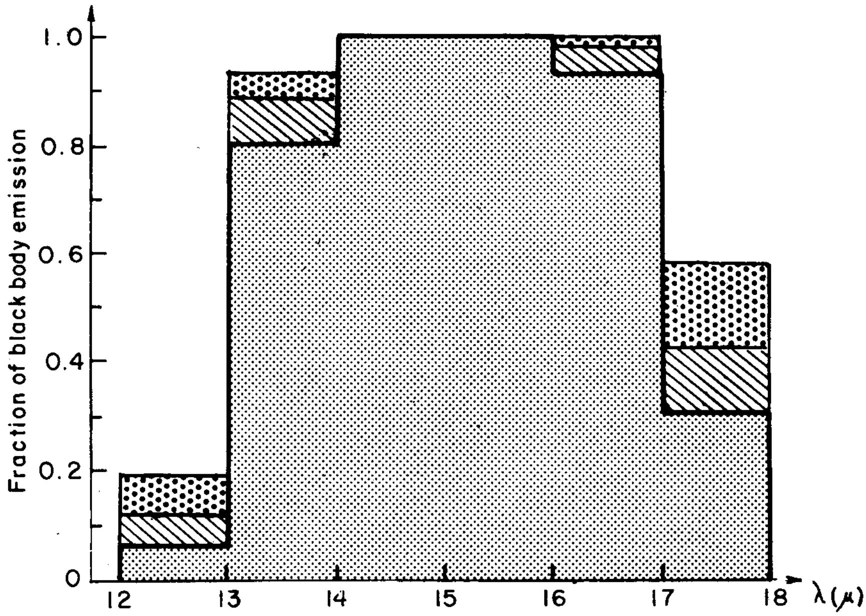


Fig. 2. The abscissa is the wave length in microns and the ordinate is the intensity of emission in percent of the black body emission. Shaded area under continuous line: present conditions. The hatched areas are the increase due to doubling, and the hatched and dotted areas the increase due to cuadrupling the CO_2 content.

Fig. 3a shows the complete emission spectrum used in the model for a temperature of 300°K. The shaded area represent the total energy emitted by the atmosphere for the present CO_2 content, the hatched areas the increase due to doubling, and the hatched and dotted areas the increase due to quadrupling the CO_2 content. The spectrum used in previous computations with the model is shown in Fig. 3b.

Using the method employed previously (Adem, 1962) we find the following expression for the atmospheric emission:

$$
\begin{aligned}
E(T^*) = \sigma T^{*4} &- F(T^*, 8\mu, 12\mu) \\
&- (1-a_1)F(T^*, 12\mu, 13\mu) - (1-a_2)F(T^*, 13\mu, 14\mu) \\
&- (1-a_3)F(T^*, 16\mu, 17\mu) - (1-a_4)F(T^*, 17\mu, 18\mu)
\end{aligned}
\tag{1}
$$

where $E(T^*)$ is the total atmospheric emission at temperature T^*; the function $F(T^*, \lambda_1, \lambda_2)$ is given by

$$
\begin{aligned}
F(T^*, \lambda_1, \lambda_2) &= \int_{\lambda_1}^{\lambda_2} c_1 \lambda^{-5} e^{-c_2/\lambda T^*} d\lambda \\
&= \left[c_1 e^{-c_2/\lambda T^*} \left(\frac{T^*}{c_2 \lambda^3} + \frac{3T^{*2}}{c_2^2 \lambda^2} + \frac{6T^{*3}}{c_2^3 \lambda} + \frac{6T^{*4}}{c_2^4} \right) \right]_{\lambda_1}^{\lambda_2}
\end{aligned}
\tag{2}
$$

where $\sigma = 8.215 \times 10^{-10}$ cal cm^{-2} ($^{\circ}$K)$^{-4}$ min^{-1} ,

$c_1 = 5.538 \times 10^5$ calμ^4 cm^{-2} min^{-1} and $c_2 = 14350\ \mu\ ^{\circ}$K .

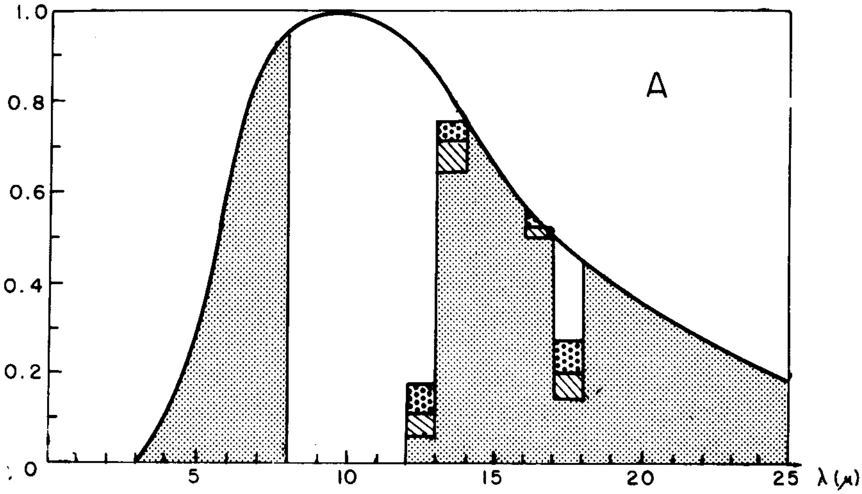
The constants a_1, a_2, a_3 and a_4 are respectively equal to .067, .802, .931 and .310 for present conditions and to .121, .885, .981 and .426 for the case when the atmospheric CO_2 content is doubled.

Assuming as in the previous work (Adem 1962), that $T^* = T_0^* + T^{*\prime}$ where $T^{*\prime}$ is a departure from a constant mean temperature T_0^* and $T_0^* >> T^{*\prime}$, formula (1) becomes:

$$
E(T^*) = E(T_0^*) + \left(\frac{\partial E}{\partial T^*} \right)_{T^* = T_0^*} T^{*\prime}
\tag{3}
$$

Since T^* is in Kelvin degrees, $T^{*\prime}$ is for atmospheric temperatures usually much smaller than T_0^*, therefore the linear formula (3) is a good approximation to the exact formula (1) and is used in the model.

Using the same method as in a previous paper (Adem 1962) and the Savino-Ångström formula for the short wave radiation from the sun and sky absorbed by the upper layer of earth (Adem 1964b), we obtain for the heating due to radiation processes, similar formulas as for the case of the atmospheric emission shown in Fig. 3b, used in all the previous applications of the model, and do not change the basic equations of the model described in a recent paper (Adem 1982).



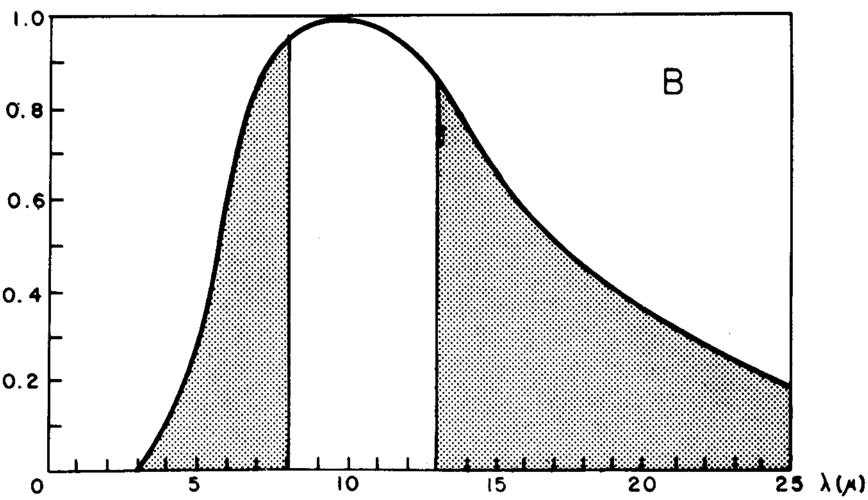


Fig. 3. Part A: The emission spectrum used in the model. The shaded areas are the total energy emitted by the atmosphere for present CO_2 content. The hatched areas are the increase due to doubling, and the hatched and dotted areas the increase due to cuadrupling the CO_2 content. Part B: The spectrum used in previous computations.

THE NUMERICAL EXPERIMENTS

The procedure used in the computations is the same as in previous experiments (Adem 1981, 1982), namely, first the normal case is computed and then the abnormal one. In this experiment first the present day climate is computed, which will be regarded as the normal case, and then the case with a doubling of the atmospheric CO_2, which will be regarded as the abnormal one. The difference between the two cases yields the departure with respect to present conditions.

The detailed model's equations and solution and the results for the present day climate are given elsewhere (Adem, 1982). The results for a doubling of the atmospheric CO_2 are given below.

We will show here only the effect on the surface temperature, which is the variable that can be compared with the estimates made by other authors, using other models.

Figure 4 shows the computed increase of surface temperature due to doubling the CO_2 content of the atmosphere, in tenths of ^{o}C for January (part A) and July (part B). This figure shows that the increase is larger in Summer than in Winter and larger in the continents that in the oceans.

Figure 5 shows the zonally averaged values, in zones of five degrees of latitude, of the increase of the surface temperature in ^{o}C, due to a doubling of the atmospheric CO_2, for Winter (dashed line), Spring (dashed-dotted line), Summer (continuous thin line), Fall (dotted line) and the annual average (continuous thick line). This figure shows that for all the seasons the increase in surface temperature becomes greater towards the higher latitudes, with the maximum value in the zone between 75 and 80 degrees of latitude, reaching there the values 2.6, 1.5, 1.2 and 0.8 ^{o}C in Summer, Spring, Fall and Winter respectively, and a maximum of 1.5 for the annual average at the same region. There is another maximum in the region from 40 to 45 degrees of latitude in Spring and Winter, with values of 1.0 and 0.6 respectively. This maximum also exists in the annual average in the same region, with a value of 0.7^{o}C. The two maxima are due to the snow-ice temperature feedback.

The averages for the whole region of integration (shown in figure 4) are 0.8^{o}C for Spring and Summer; and 0.6^{o}C for Fall and Winter. Therefore, the computed annual average of the increase in the surface temperature is 0.7^{o}C. This value is similar to those computed by Weare and Snell (1974), and Rasool and Schneider (1971) who obtained values of 0.7 and 0.8 respectively. Estimates by other authors are considerably larger (Möller, 1963, Manabe and Wetherald 1967, 1975, 1980;

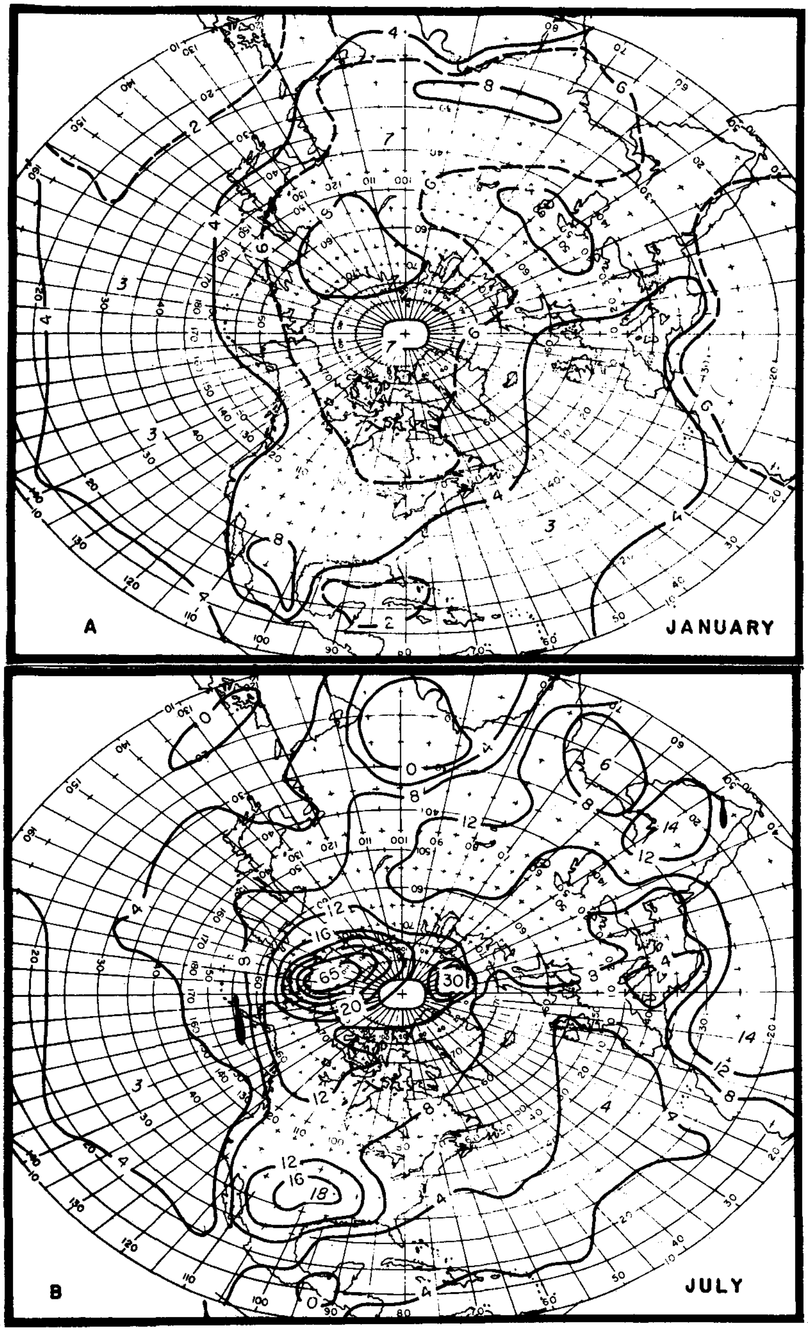


Fig. 4. The computed increase in surface temperature due to a doubling of the atmospheric CO_2, for January (A) and July (B), in tenths of ^{o}C.

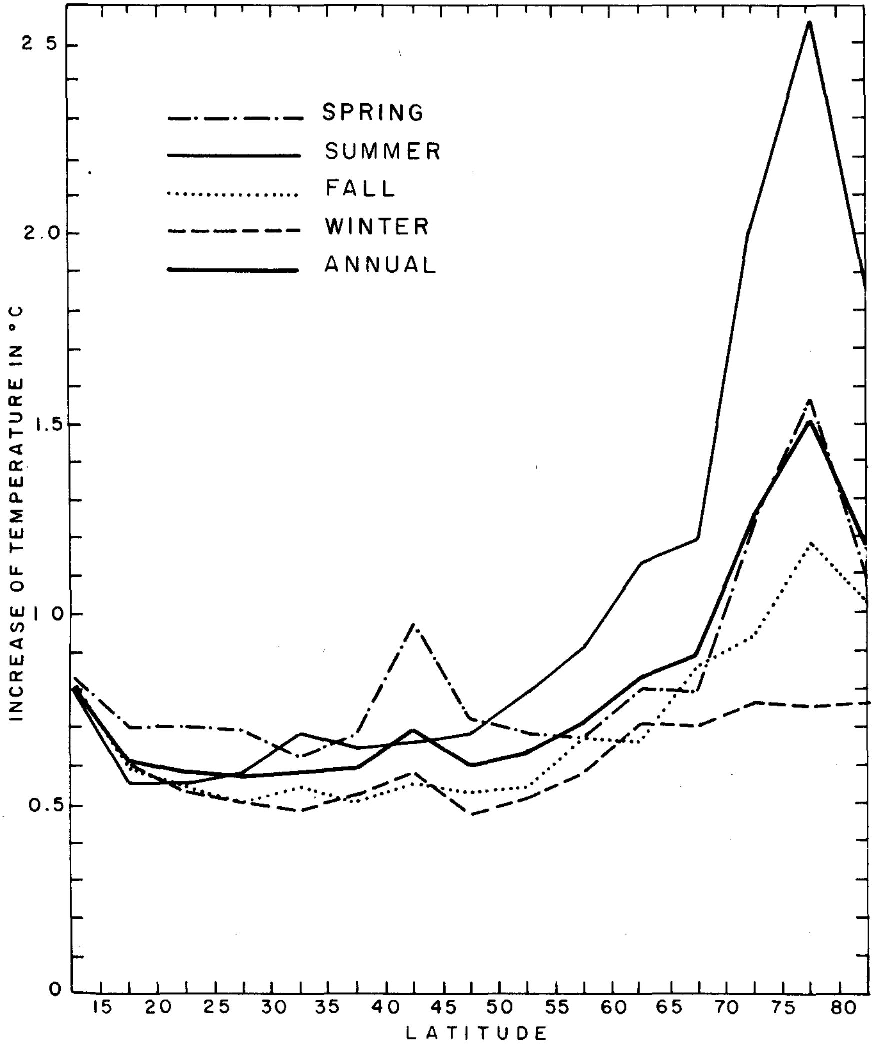


Fig. 5. Zonally averaged values of the increases of surface temperature due to a doubling of the atmospheric CO_2 for the four seasons of the year, in tenths of ^{o}C.

Ramanathan *et al.*, 1979). Some of them were summarized by Schneider (1975) who concluded that the increase is of 1.5 to 3.0°K. Furthermore Augustsson and Ramanathan (1977) and Watts (1978) estimated that the increase is of 2.0 to 3.2°K and 2.0 to 6.5°K respectively.

In our model, we have used an ocean mixed layer depth of 100 m coupled with an atmospheric layer; and the ocean surface temperature is computed together with the atmospheric temperature. To determine the effect of the ocean mixed layer we have carried out computations for two additional cases: one in which the depth of the mixed layer is equal to 25 m and another in which the mixed layer depth is infinite, and therefore, the surface ocean temperatures are prescribed as the observed normal monthly values. The monthly warming corresponding to these models is shown in Fig. 6, where the dashed line corresponds to the depth of 25 m and the dotted line to the case of infinite depth. The solid line corresponds to the case of 100 m.

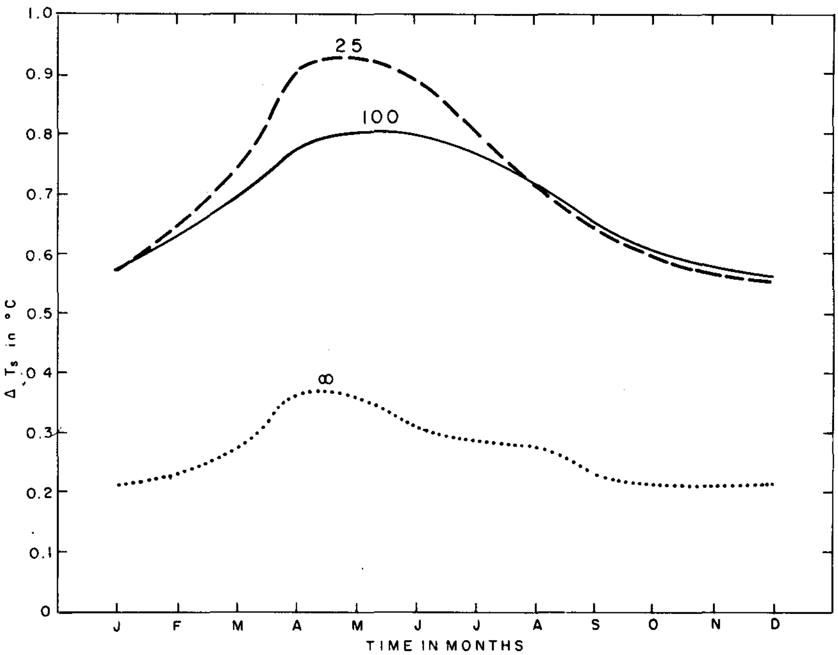


Fig. 6. Surface temperature warming, in ^{o}C, due to a doubling of the atmospheric CO_2, computed with a model that has an ocean mixed layer of 25 m. (dashed line), 100 m (solid line) and of an infinite depth (dotted line).

Table 1 shows the seasonal and annual values of the warming for models of different depth of the mixed layer. This table and Fig. 6 show that the warming decreases as the depth increases. However, in the range of values of the mixed layer from 25 to 100 m the difference are so small that the warming is essentially the same and equal to about .6^{o}C in Winter and Fall and .8^{o}C in Spring and Summer, with an annual value of about 0.7^{o}C.

The warming for an infinite depth of the mixed layer is much smaller than the one of the models with the realistic mixed layer depth. In this case the annual warming is of only .25°C in agreement with the values of .33°C obtained by Gates *et al.* (1981), who used also an infinite ocean mixed layer.

Table 1

Surface temperature warming (ΔT_S) due to a doubling of the atmospheric CO_2 for different depths of the ocean mixed layer

Depth of mixed layer (meters)	ΔT_S (°C)				
	Winter	Spring	Summer	Autumn	Annual
25	.59	.85	.80	.60	.71
100	.59	.76	.76	.61	.68
∞	.22	.33	.29	.22	.26

It is interesting to point out that the convergence of the solution depends on the depth of the ocean mixed layer. In the case of a depth of 100 m, 13 years of model run were needed while for depth equal to 25 m and ∞, only 4 years and 3 years were needed respectively. This is shown in Fig. 7, where the abscissa is the number of years that the model has been run and the ordinate is the warming due to doubling the atmospheric CO_2. The dashed, solid and dotted lines represent the solution for 25 m, 100 m and ∞ respectively. The solution is shown with an encircled dot. The convergence for a depth of 25 m is faster than for a depth of 100 m because the heat storage capacity has been reduced allowing a faster steady state solution. However, in the case of an infinite depth the convergence is very fast because the ocean temperature is prescribed and not allowed to vary.

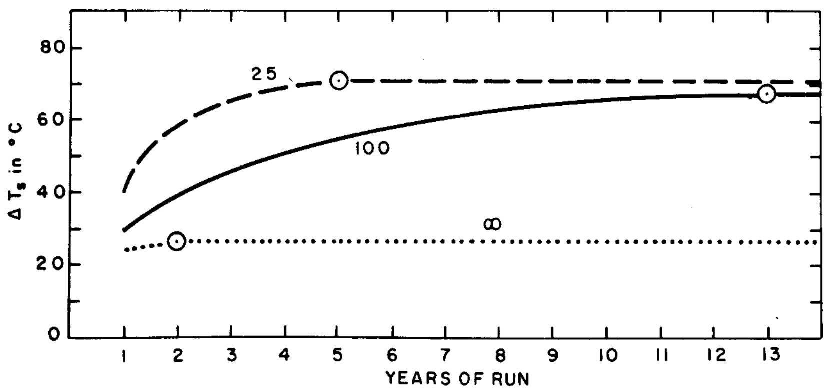


Fig. 7. Convergence of the solution as a function of the depth of the ocean mixed layer. The abscissa is the number of years that the model has been run and the ordinate the warming due to a doubling of the atmospheric CO_2. The dashed, solid and dotted lines are the solutions when 25 m, 100 m, and infinite are used as mixed layers depths respectively.

The annual increase of 0.7°C in surface temperature that our model computes is smaller than the recent value of 2°C obtained by Manabe and Stouffer (1980), who also used the model with an ocean mixed layer and with a seasonal variation. In order to investigate the cause of this discrepancy we have carried out an experiment to determine the effect of neglecting the variations of the heating different from radiation. The results are shown in Fig. 8 where the dashed line is the computed annual average surface temperature increase for the case when the variation in the heating different from radiation (evaporation at the surface, sensible heat given off from the surface to the atmosphere and condensation of water vapor in the clouds)

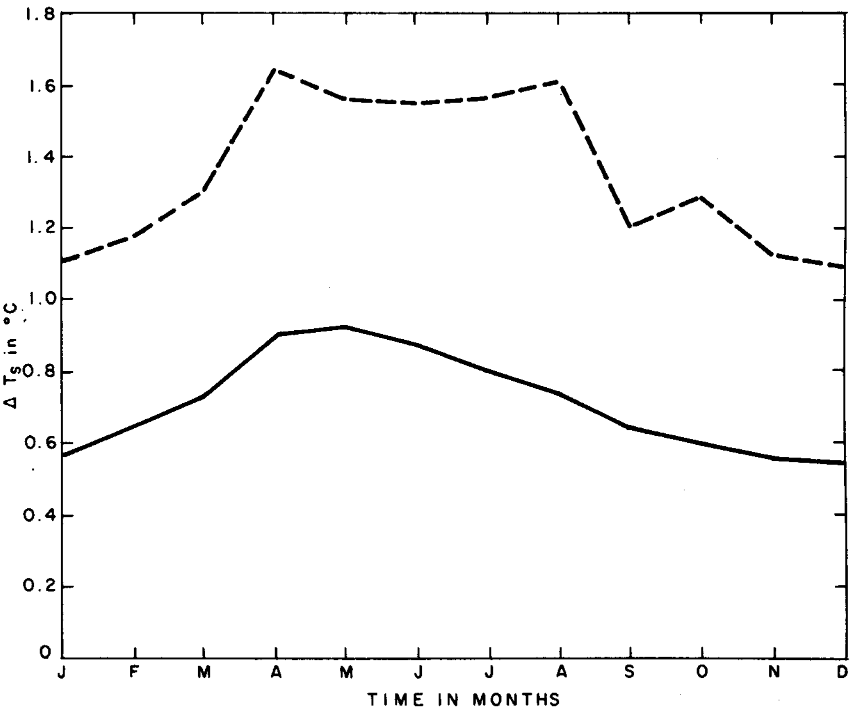


Fig. 8. Surface temperature warming, in °C, due to a doubling of the atmospheric CO_2, computed with a model which does not include variations due to heating different from radiation (dashed line); and one which includes them (continuous line).

is taken as zero in the model. In this case the computed annual average is 1.4°C which is a value closer to the one obtained by Manabe and Stouffer (1980). Comparison with the case in which the heating different from radiation is included (solid line) shows that the effect of the variation of this heating is to reduce in one half the computed surface temperature increase. The parameterizations used for these heating components are very crude, and were originally developed for use in a model for monthly climate prediction. Furthermore, the evaporation at the surface and the condensation of water vapor at the clouds were parameterized independently and violate the conservation of water vapor, which is critical in these long term integrations (Adem 1965a). For these reasons we believe that a more refined parameterization of the heating different from radiation will yield a more realistic value for the increase in surface temperature due to a doubling of the atmospheric CO_2.

The results presented here should therefore be considered very preliminary. The purpose of the paper has been to introduce this new approach for computing the effect of the increase of CO_2 in the climate of the Earth and to show the importance, in the solution, of including an ocean mixed layer and of using adequate parameterizations for the heating functions. Improvements are expected as soon as we are able to run a new version of the model, now being developed, which includes revised parameterizations.

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